Site-Specific Nutrient Management

For Nutrient Management Planning To Improve Crop Production, Environmental Quality, and Economic Return

Phosphorus: Chapter 3 of 10

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Chapter 3:
Phosphorus Management

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Introduction

Phosphorus (P) is an essential nutrient for crop production since it is required for many plant functions, including energy transfer and protein synthesis. Phosphorus is included in adenosine phosphates (ADP and ATP) that play a crucial role as "energy currency" within plants. It is also a component of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), which contain the genetic code of the plant. Adequate P supply is associated with increased cell multiplication, stem and root growth, stem strength, nitrogen (N) fixation capacity of legumes, and grain yield. The most common visual symptoms of P deficiency in plants include overall stunting and, in with extreme deficiency, dark green/purple coloration of leaves.

Phosphorus uptake and removal from fields with harvest are highly dependent on yield and to a lesser extent the tissue P concentration, although amounts typically are much less than for N or potassium (K). Table 1 shows, as an example, the Iowa guidelines concerning P concentration per unit of yield for several crops. Commercial P fertilizer analysis has historically been expressed as the oxide form (P_2O_5) rather than the elemental form (P), therefore P uptake and removal values usually are expressed as P_2O_5 per unit of yield. Using the ratio of their molecular weights, $\%P_2O_5$ can be converted to %P by multiplying by 0.44 ($\%P = \%P_2O_5 \times 0.44$). To more accurately estimate P_2O_5 uptake or removal for a specific situation, one can have P analyzed in the plant tissue that is removed from the field, and multiply the result by the dry matter yield removed. The estimate of P that is being removed by the crop can help in determining P fertilization recommendations to maintain desirable soil-test P levels.

Table 1. Phosphorus amounts in harvested portions for selected agricultural crops.

Crop	Unit of Yield	Pounds P_2O_5 per unit of yield
Corn	bu	0.37
Corn silage	bu grain equivalent	0.55
Soybean	bu	0.80
Oat and Straw	bu	0.40
Wheat	bu	0.60
Sunflower	100 lb	0.80
Alfalfa	ton	12.5
Tall fescue	ton	12.0

Source: Iowa State University Extension publication PM 1688.

In some regions with short histories of grain-crop production and little application of animal manures, soil-test P levels are low and crop response to P application is very likely. In most regions of the U.S., however, the natural amount of crop-available P in soils has been increased due to long-term application of P fertilizer or animal manure. When soil P levels become excessive, the danger of freshwater eutrophication increases, which is now one of the most common water quality impairments in the humid regions of the U.S. and many developed countries. Recent outbreaks of harmful algal blooms (e.g., *cyanobacteria* and *P. fiesteria*) have increased society's awareness of eutrophication and the need for solutions. The concentration of specialized farming systems has led to a P transfer from grain- to animal producing areas. This transfer has created regional surpluses of P inputs as fertilizer and feed, increases of soil P in excess of crop needs, and increased risk of P loss from land to surface waters. The overall goal of efforts to reduce P loss to water should be to balance P inputs and outputs at farm and watershed levels, while managing soil and P in ways that maintain or increase productivity. Management strategies that minimize P loss to surface water may involve optimizing P use efficiency by using soil testing and proper P application recommendations, variable-rate application, transport of manure from areas with surplus to areas with P deficit, and implementation of soil conservation practices to reduce erosion and runoff.

In order to improve P management in agricultural systems, however, it is important to first understand the main P processes that occur in the soil-plant system.

Basic Phosphorus Processes in the Soil-Plant System

Phosphorus in Soils

Phosphorus exists in the soil as dissolved orthophosphate in solution (mainly HPO_4^{-2} or $H_2PO_4^-$ depending on soil pH), sorbed P on the surface of organic or inorganic compounds, or as part of organic P compounds or P minerals. The dissolved phosphate ion is the only form that plants can take up, yet in the surface layer of most agricultural soils there is less than 1 mg/L (1 ppm) of dissolved phosphate in the soil solution (soil water), except in recently fertilized soils. On the other hand, the total soil P concentration can vary from about 200 to 2,000 ppm depending greatly on soil parent material and histories of cropping and fertilizer or manure application. Organic P normally represents about 25 to 65% of total P in surface soils, depending mainly on soil organic matter content. Organic P usually decreases abruptly with soil depth, paralleling decreases in organic matter. The processes that control the amount of plant available P in the soil are plant uptake, sorption/desorption, mineralization/immobilization, precipitation/dissolution, runoff, and leaching. Because of the usually very small concentration of P in the soil solution, an understanding of these processes is important for implementing good P management.

Phosphorus retention in soils

Inorganic P dynamics in soils are dominated by processes of sorption/desorption and precipitation/dissolution. Sorption refers to the binding of P to the surface of soil particles. Phosphorus sorption/desorption reactions are strongly influenced by soil pH, texture, and mineralogy of fine soil particles. For example, orthophosphate reacts strongly with aluminum (Al) and iron (Fe) oxides and hydroxides, especially at low pH, and also with carbonates in high-pH soils. Fine textured soils generally can sorb more P because they have higher clay concentration and greater surface area. Dissolved organic compounds from recent organic matter additions can increase P availability by blocking sites or coating Fe/Al oxides. Phosphorus desorption generally increases as solution P decreases due to plant uptake or leaching, and also under flooded or waterlogged conditions due to changes of Fe hydroxides and oxides to more soluble forms. When high P fertilizer rates are applied, P sorption sites can become partially saturated, which increases the recovery of added P but can also increase dissolved P loss through the soil profile or surface runoff.

Precipitation/dissolution reactions occur at the same time as sorption/desorption, although not necessarily in the same volume of soil. Precipitation takes place mainly when a water-soluble P source increases the concentration of phosphate in the soil solution, and it forms compounds with cations added with the P source or already present in the soil solution. Dissolution occurs mainly when added, recently formed, or native P compounds dissolve as a result of decreases in the concentration of soluble phosphate in solution. The P precipitation/dissolution reactions are largely dominated by a variety of calcium phosphates (Ca-P) in neutral to high-pH soils and by Al and Fe phosphates (Al-P and Fe-P) at pH levels below about 6.5. Reactions of ammonium phosphates or potassium phosphates temporarily can dominate, however, when fertilizers containing these compounds are added to the soil.

When a water-soluble P fertilizer is added to moist soil, a solution with a very high phosphate ion concentration develops at the application point (granule or band), and in the immediate vicinity an acid or alkaline condition depending on the fertilizer material. This solution is very acid (pH 1 to 2) for superphosphate fertilizers (mono-calcium phosphates), moderately acid (about pH 4) for mono-ammonium phosphate (MAP) fertilizer, and alkaline (about pH 8) for di-ammonium phosphate fertilizer (DAP). This concentration of phosphate diffuses away from the application point, and intense reactions occur with soil constituents. The phosphate concentration in the soil solution decreases over time, the original soil pH at the application point is restored, and much of the added P becomes retained by the soil particles (sorbed or precipitated) but still has high plant-availability. Therefore, added P does not have a long-term effect on soil pH. Large application rates of MAP or DAP can acidify soil, however, because of the nitrification of ammonium contained in these fertilizers.

Over a few weeks or months (depending on soil chemical and mineralogical properties) some of the applied P may become strongly retained and therefore less available for crops. Soils with high levels of calcium carbonate may strongly retain a higher proportion of added soluble P due to more adsorption to carbonate surfaces and transformation of initially soluble Ca phosphates to less soluble forms. Soils with high levels of Fe-oxides (soil can be strongly or moderately acid) may strongly retain a higher proportion of added soluble P due to high adsorption to oxides surfaces and transformation of initially soluble Al or Fe phosphates to less soluble forms. Therefore, in general and under otherwise similar conditions, P is most readily available between pH 6 and 7 (Figure 1). In many soils and outside that pH range, however, the retention is reversible. As soluble P is taken up by plants, retained P replenishes the low concentration of soluble P and, therefore, acts as a reservoir for plant available P supply.

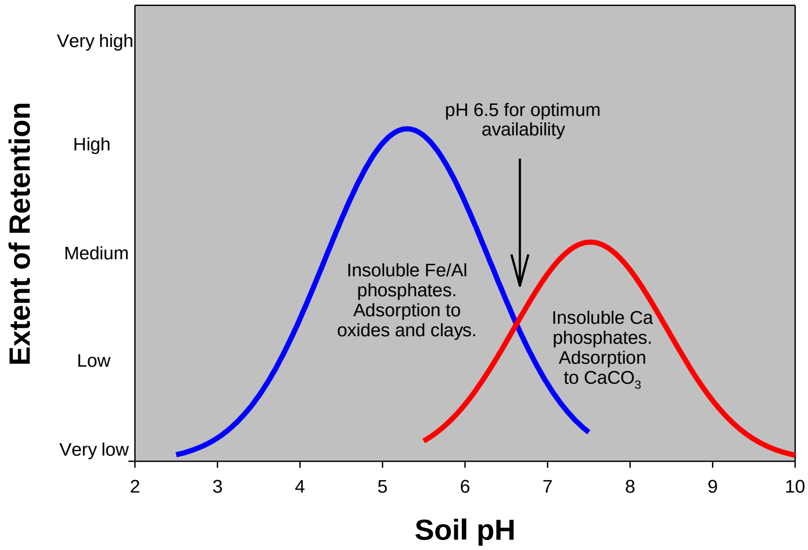

Figure 1. The effect of soil pH on P retention and availability.

Mineralization and immobilization

Phosphorus mineralization is the process by which organic P becomes converted to phosphate ions as organic materials decompose, and immobilization is the process by which soluble P becomes tied up in microorganism cells. In the U.S., annual P mineralization in soils has been found to range from 4 to 22 lb P_2O_5/acre/year, which can represent a significant portion of crop P uptake in some situations. Mineralization occurs most readily when the C:P ratio of a material is less than 200:1, and immobilization occurs when that ratio is greater than 300:1. Mineralization and immobilization of P are affected by temperature, moisture, aeration, and pH in similar ways as N mineralization and immobilization, because they involve microbial and enzymatic processes. In practice, however, and with a few exceptions, the importance of P mineralization/immobilization is much less than it is for N. This is because in most soils, the inorganic P reactions dominate and have the greatest influence on plant P availability. There are exceptions where organic P mineralization/immobilization can have a major influence on plant available P. These include large application of organic materials with very high or very low P concentration, tillage of permanent hay or pastures in soils with moderate to high P levels (net mineralization), or when soils with low organic matter from many years of improper cropping and erosion control are changed to pasture/hay or no-till management with relatively low P fertilization rates (net immobilization).

Phosphorus: A Relatively Immobile Nutrient

As a result of the P reactions and processes in soils, P moves slowly and only short distances. The amount of P that reaches the root surface with water mass flow is not sufficient to supply plant needs, and phosphate ion diffusion through the soil solution is the main mechanism of plant P uptake. This characteristic has several important consequences. From a plant uptake perspective, factors that limit the rate of P diffusion and both the rate of root growth and the size of the root system can limit P uptake. These include cold temperature and low moisture (which limit diffusion and root growth), soil physical properties that inhibit root growth, and diseases or pests that impair root function. Therefore, induced P deficiency may occur even with adequate soil-test levels. In these situations, or when there is strong soil P retention, placement that puts applied P near young plant roots (starter, banding) may increase plant growth and yield compared with broadcast application.

The typical retention of P by soil also makes soil erosion the most important P loss pathway from fields, and this can occur from water or wind erosion. For example, assuming a total soil P concentration of 500 ppm, soil erosion at 5 ton/acre would represent about 10 lb P_2O_5/acre, a substantial loss in the overall P budget. Some eroded soil from upwind or upstream may be deposited to replace a portion of that lost, although rarely is the redistribution of eroded soil uniform within fields or at field borders. Dissolved P loss with surface runoff water can represent another loss of P from agricultural fields. However, the concentration of dissolved P in runoff is generally quite low due to the high level of P sorption and precipitation. One exception would be for runoff events immediately or shortly after applying P fertilizers or runoff from animal feedlots. Some factors contributing to soil erosion and surface runoff include long slopes in fields farmed without conservation structures, tillage or crop rows up and down moderate or steep slopes, inadequate canopy or crop residue cover, lack of windbreaks, intensive tillage, and over-irrigation.

The amount of P loss with leaching through the soil profile is much less than P loss with erosion and surface runoff in most soils and landscapes. In coarse-textured soils or in moderately textured soils with sustained P application in excess of crop removal (very high soil test P), fertilizer or manure applications can increase subsoil P concentrations and leaching to groundwater or surface waters through subsurface tile drainage. Also, P leaching can be a concern on coarse-textured soils that are frequently flood-irrigated or regions with high rainfall. Therefore, P leaching can result in water quality impairment in some situations.

Phosphorus Soil Testing

Soil testing is a very useful tool to assess P requirements for crops. Several test methods are used in different regions of the country because some adapt better to different soils. The most widely used tests are Bray-1, Mehlich-1 (in the southeast), Mehlich-3, Morgan (in the northeast), and Olsen (mainly in the northern Great Plains and western states). Most of these tests are well adapted to acid to neutral soils, but the Olsen is better suited for high-pH, calcareous soils. Soil samples are generally collected from the upper 6 to 8 inches of soil because P from fertilizers and manure will stay in this upper layer, most crop rooting and uptake occurs in this soil layer, and this sampling depth usually better predicts P fertilization needs. All soil-test methods need to be correlated and calibrated with crop yield response in order to give a meaning to the test result in terms of crop sufficiency. Different methods and sampling depths result in different test results, and even the same method may have a different calibration in soils with contrasting mineralogy and chemical properties.

Research has been and continues to be conducted in different regions to correlate and calibrate soil test methods. Figure 2 shows the general relationship between soil-test P levels and crop yield. Soil test levels are generally distributed into interpretation categories referred to as very low, low, medium (or optimum), high, and very high (or excessive). The "critical" level or range separates soil-test values for which there is a high probability of large to moderate crop response to fertilization from values for which there are small and infrequent responses. The critical level can vary with the test method, crop, soils, and climate; and sometimes even with the philosophy of researchers that establish interpretations and recommendations. For example, the Bray-1 P level considered adequate for crops, and at which no fertilization is recommended, vary from about 12 to 30 ppm for forages or grain crops across the U.S. In addition, because nutrient and crop prices influence the profitability of nutrient application and crop production, economic considerations together with producers' management and business philosophies further influence the optimum soil-test levels for crops. The optimal soil-test P level from an economic perspective will depend largely on the nutrient and fertilizer price ratios, producer management, and other enterprise decisions.

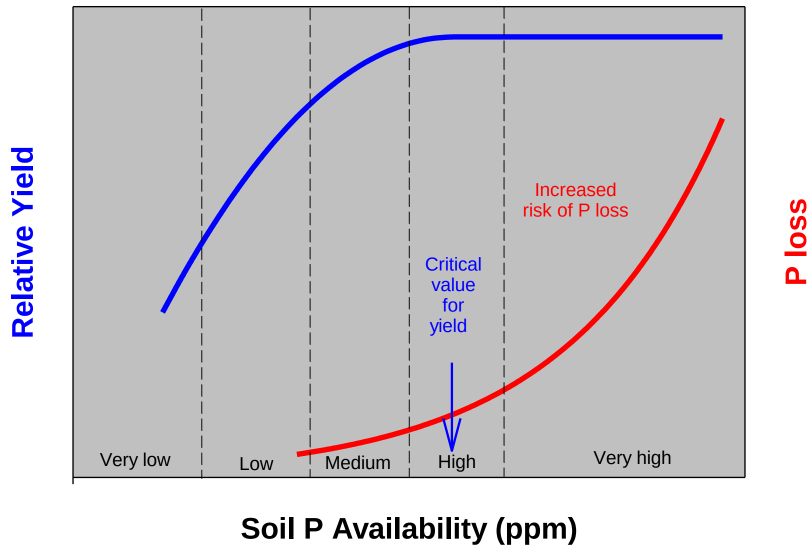

Figure 2. Schematic representation of the relationship between relative crop yield and P loss.

Interpretation of soil-test P values for water quality issues must be different than for crop production. There is general agreement that soil-test levels higher than adequate for crops may significantly increase the risk of P loss and water quality impairment. As an example, Figure 2 also provides a schematic representation of the relevance of soil-test P values for crop yield and risk of P loss. There is no agreement on what this threshold should be for different regions or production systems. Also, most scientists agree that the soil-test P level is only one of several factors that affect P loss and transport form agricultural fields. Therefore, risk of loss should be considered in a comprehensive P risk assessment tool, such as the P index.

Phosphorus Interpretation and Recommendations Concepts

Soil test laboratories, universities, and crop consultants provide guidelines for application rates based on soil P test results. Interpretation of test results and the recommended fertilization rates vary greatly across regions due to different crop, soil, or economic relationships related to crop response to nutrient application but also concepts and assumptions concerning nutrient management. The concepts of sufficiency level and buildup/maintenance for P and other immobile nutrients have been discussed in soil fertility circles for several decades.

According to a strict sufficiency level concept, the nutrient application rate for any given soil test P level should be the one that results in maximum yield or maximum economic yield. The amount of nutrient to apply is determined from many field trials on different soils over many years. This approach emphasizes short-term profitability from fertilization; high returns per pound of fertilizer applied, and reduced risk of fertilizer over-application by accepting a moderate risk of yield loss. It requires frequent use of soil-testing and a research data base that adequately predicts a crop response under good or normal conditions.

A strict build-up and maintenance concept emphasizes increasing soil-test levels to an optimum level in a short period of time by applying rates higher than those for a one-year rate needed to achieve maximum yield or maximum economic yield. This approach reduces the risk of yield loss due to insufficient nutrient levels, emphasizes long-term profitability from fertilization, and supports the maintenance of optimum or slightly higher than optimum soil-test levels. It may not require frequent soil testing, but requires knowledge of fertilizer rates needed to maintain soil-test values over time, which usually is based on calculated P removal with crop harvest. A yield response or profit to maintenance fertilization usually is not expected.

The interpretation and fertilizer recommendations systems used across the U.S. seldom strictly follow these two concepts, and actually combine both to different degrees. For example, recommendations by the University of Illinois are closer to the buildup/maintenance concept, those in Minnesota are closer to the sufficiency level concept, and those in Iowa are intermediate. Kansas, however, provides interpretations for both concepts. The main reason for use of the buildup and maintenance approach is that many soils retain applied P but do not necessarily "fix" much P in forms unavailable for crops, and this allows for both buildup and drawdown as management options within the cropping system. For example, Figure 3 provides an example of long-term soil-test P trends over time for various fertilization rates in a typical Iowa soil with a corn-soybean rotation. Data in this figure also demonstrates two important characteristics of soil-test P and fertilization relationships observed in many soils of the U.S. (but not necessarily all). One is that with prevailing crop and fertilizer prices, moderate soil-test P buildup happens even with economically optimum rates applied to low-testing soils. This is explained by only partial plant P uptake of applied fertilizer, P recycling to the soil with crop residues, and soil properties that keep applied P mostly in crop-available forms over time. The other important characteristic is that it usually takes higher P application rates to maintain a high soil-test P level than low or medium levels. This occurs because of increased P concentration of harvested products with increasing soil-test P (luxury P accumulation) and increased P loss through erosion, surface runoff, or leaching through the soil profile.

The keys for developing sound soil-test P interpretation and nutrient application guidelines includes information on crop response to fertilization and calibration of soil-test methods; profitability of fertilization for different soil-test interpretation categories; long-term soil-test P trends as affected by fertilization, yield levels, removal, and plant-tissue P concentrations; and impacts of soil-test P levels on water quality. Additional consideration of management philosophies, land tenure, and attitudes toward risk (related to yield loss or gain, short-term or long-term profitability, and environmental impacts) can influence development of soil-test P interpretations and P fertilization practices suitable to a large variety of soils, production conditions, and producer management philosophies.

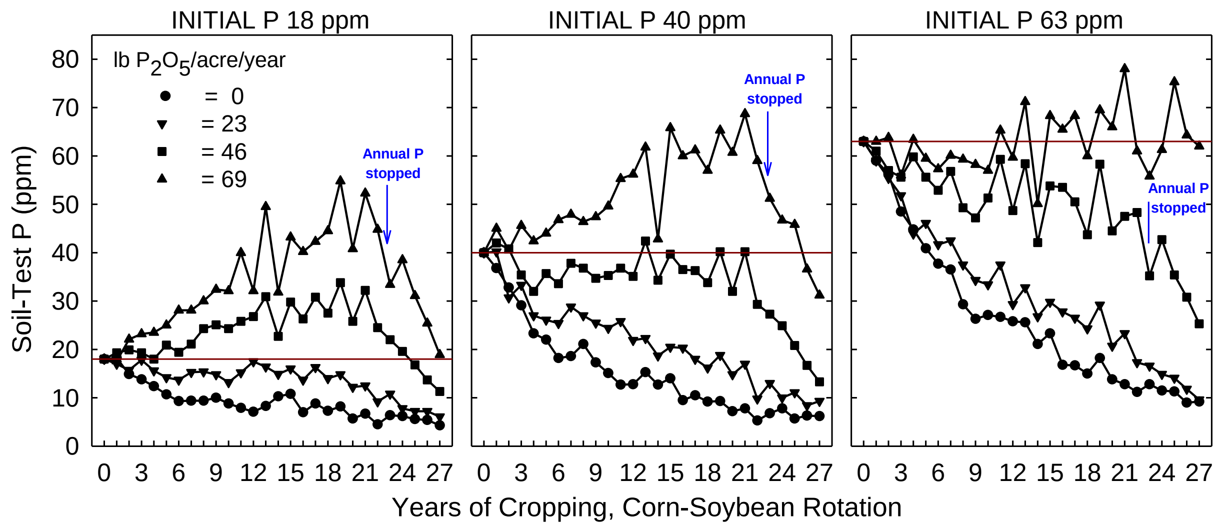

Figure 3. Change in soil-test P (Bray-1) over time with different initial soil-test levels and annual P fertilizer rates in a corn-soybean rotation. Adapted from Mallarino, A.P. 2009. Long term phosphorus studies and how they affect recommendation philosophies. p. 6-12. In North-Central Extension-Industry Soil Fertility Conf. Proceedings. Nov. 14-15. Vol. 25. Des Moines, IA.

Phosphorus Fertilizer and Manure Management

Proper management of P applications is a key for optimizing yield, profitability, and water quality. There are some considerations regarding P source, timing, placement, and rate that producers should consider in order to maximize P use efficiency.

<u>Phosphorus sources</u>

The two most commonly used commercial P fertilizers in the U.S. are MAP (monoammonium phosphate) and DAP (diammonium phosphate). There is no strong research data indicating different efficacy for these products as long as the total P and N rates applied, and the application method and timing are the same. The slightly different manufacturing processes and different temporary pH when applied to the soil do not result in clear P efficiency differences. Nitrification of ammonium in both fertilizers may result in more acidic pH when using DAP, but this difference is negligible for normal P application rates and given the much higher impact of the comparatively higher N fertilization for cereals.

Use of triple superphosphate (sometimes referred to as concentrated superphosphate) in the U.S. has decreased greatly during the last two decades, and is difficult to find in many regions. This excellent P source, and also simple superphosphate (which contains sulfur), are very important P sources in other parts of the world, however. Use of ammonium polyphosphate and other polyphosphates in fluid fertilizers is very common in the U.S. (such as in 10-34-0 and other mixtures). This P source hydrolyzes rapidly in soil to phosphate after application (even partially during long storage) and, therefore, undergoes similar sorption and precipitation reactions described for other P sources. Rock phosphate, which is comprised of apatite and fluorapatite, is used only infrequently in the U.S. due to the low solubility of these two minerals, especially at high pH. Organic producers frequently use this form of raw, unprocessed P mineral as a nutrient source, but at very high rates and pulverized into fine particles due to its low solubility and low available P concentration. Rock phosphates that are most suitable for direct application are used extensively in other parts of the world, however, mainly for forages and pastures in acidic soils.

Applying manure to cropland sometimes presents different management issues and options from those discussed above for P fertilizers. If manure is applied to meet crop N needs, more P may be applied than is necessary to meet crop P needs. However, this varies greatly with the animal species and both feeding and manure handling systems due to large impacts on the N:P concentration ratio in manure and the plant availability of the manure N. Therefore, long-term manure applications may increase soil test P levels well above critical levels, especially when applied to continuously to cereal crops to meet N fertilization requirements. The crop-availability of manure P varies less than N, is less prone to large losses and the significant transformations typical with manure N. However, plant P availability is affected by the animal species and diet. Suggested manure P crop-availability values vary greatly across the U.S. Iowa research has shown, for example, that the crop-availability of manure P compared with inorganic fertilizer ranges from 60 to 100 % for beef or dairy manure and 90 to 100% for poultry or swine manure.

Manure management has become more of an issue the last few decades as crop and animal operations have become concentrated in various regions of the country and because of public and government concerns about manure management impacts on water quality. Environmental concerns related to confined animal feeding operations (CAFOs) have become an issue in the humid regions of the U.S. Phosphorus from animal manure should be managed as carefully as P fertilizer, with practices including:

representative manure samples analyzed to determine nutrient concentrations; choose the manure application rate according to crop nutrient requirements and for the crop availability of all manure nutrients (not just for P); for manure P application rates consider the nutrient needs of crop rotations rather than just individual crops; allocate manure to fields or within-field areas based on soil tests and crops to be grown; consider the risk of P loss for the field or within-field areas by using a P risk assessment tool (such as the P Index); and do not apply manure to snow-covered, frozen, or water-saturated sloping ground when runoff risk is high.

Application Rate and Placement Method

Applying P fertilizer at rates higher than crop production requirements according to soil-test calibrations and concepts discussed before is unwise from both environmental and economic viewpoints. There is no agronomic justification for building P soil test levels higher than crop sufficiency levels. Phosphorus losses in surface runoff have been shown to increase with increased P application rates. Therefore, once the crop sufficiency levels have been reached, P applications should be made only as dictated by soil testing and crop removal.

Phosphorus banding is recommended over broadcast and incorporated applications in soils that strongly retain or transform applied P into forms that have low crop availability. Because banding reduces the interaction of applied P with soil, P plant availability is enhanced and may increase use efficiency. Most of the soils of the U.S. Corn Belt and eastern U.S. do not retain P so strongly, however, and research has shown no large or consistent differences among P application methods (surface broadcast, broadcast and incorporated, banded) with tillage or no-till management, except for soils with small acreage and for starter fertilizer under some conditions. Even in these regions, however, banded P near the root zone almost always enhances early crop growth, and tends to be more efficient at extremely low soil-test P levels and with sub-optimal P application rates. In other regions or under special situations, banding is a more efficient practice and provides benefits that more than offset the additional application cost. These situations include soils with very high soil retention capacity, low rainfall regions, crops with a taproot type of root system, or when root growth is limited. Figure 4 shows a generalized schematic representation of the different types of outcomes for broadcast and band P application. Reasons for the differences in response relate mainly to soil properties, but also the crop and management practices. Local research should be used to help guide decisions for best P placement and application methods for different soils and crops.

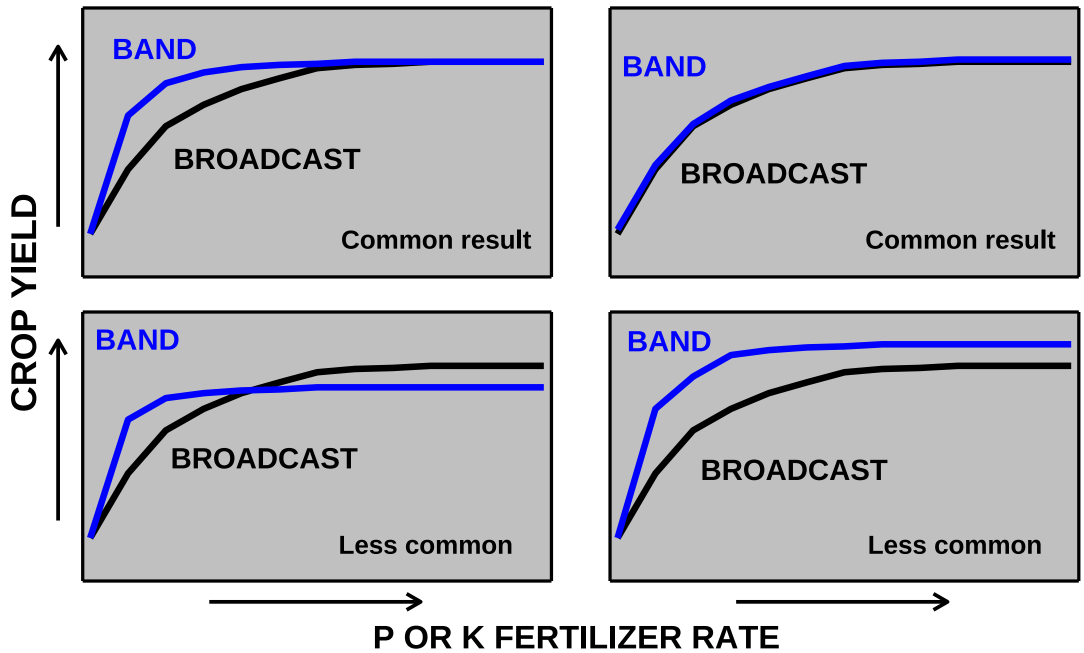

Figure 4. Idealized possible differences between broadcast and band P placement methods depending on crops and soil properties. Adapted from Black, C.A. 1992. Soil fertility evaluation and control. Lewis Publishers.

Phosphorus placement may have important implications for risk of P loss with soil erosion and surface runoff. The main concern with surface application of P is the increase in soil test P at the soil surface; at the soil-runoff water mixing zone and where water or wind erosion occurs. The surface soil P buildup may result in short-term (after a large runoff event shortly after application) or sustained long-term contribution to risk of P loss. The main concern with P incorporation by tillage is the risk of increasing the rate of soil erosion in sloping lands. Subsurface P application, without reducing P use efficacy by crops, increasing soil or water loss, or an inordinate increase in application costs, would be an ideal management practice for P.

Total runoff P loss may or may not be reduced with incorporation or subsurface injection of manure or fertilizer P compared with surface application because loss also depends on the slope, soil hydrology, P rate, and impacts of incorporation or injection on erosion and surface runoff. Generally, dissolved P in runoff is higher with surface P application if the runoff event occurs shortly after application. However, the increased risk with surface application decreases in the days and weeks following application.

Figure 5 demonstrates the effects of P rate, incorporation into the soil, and days after P application on the risk of P loss with surface runoff. Reduced P loss occurs with lower P rates, a delay in runoff events after application due to time for retention by soil constituents, and incorporation into the soil. Similar results were observed for inorganic fertilizer and poultry manure. The P loss can be greatly reduced by incorporation of large P amounts into the soil when the tillage operation does not significantly increase erosion and surface runoff mainly with runoff events shortly after application.

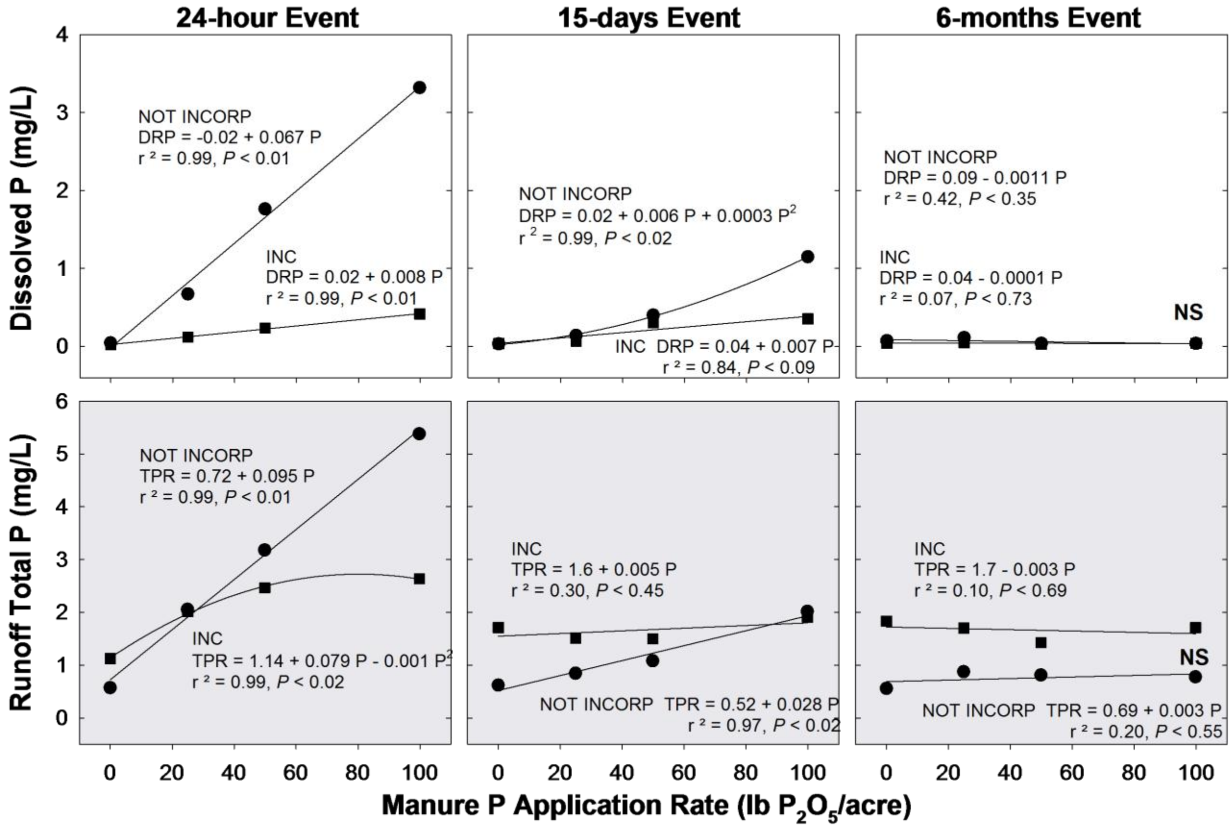

Figure 5. Effect of liquid swine manure P application rate, incorporation, and time (days after P application) of simulated rainfall on runoff P loads (NS indicates no interaction between P rate and incorporation). Adapted from Allen, B.L., and A.P. Mallarino (2008). J. Environ. Qual. 37:125-137.

Time of Application

From a nutrient use efficiency perspective in humid regions, the time of P application before the crop planting date generally is a much less important factor than the time of N application. With the exception of regions that have soils with very high P retention capacity, the timing of P application before planting has little or no impact on P use efficiency by crops. This fact justifies, for example, widespread fall P application for summer crops in the Corn Belt and the Great Plains and also application every other year for some rotations. In soils that retain or transform applied P into forms of low crop availability, however, application well in advance of crop growth may reduce P use efficiency and there are often large differences due to placement method (less efficiency with broadcast and incorporated application, for example). On the other hand, in-season P application is not recommended, except for forages crops and pastures, which is in clear contrast to N sidedress application. Many years of research has shown that an adequate P supply is important early in plant growth, to stimulate development of photosynthetic leaf area and increase grain sink size to maximize yield and P use efficiency.

The time of P application to the soil surface or of tillage to incorporate broadcast P may have a significant impact on runoff P loss shortly after application. As was shown in Figure 5, P loss with surface runoff from surface P application decreases significantly with a delay in the runoff event. A few days are needed so that soluble P reacts with the soil and the phosphate concentration in solution decreases. Therefore, the importance of incorporation and the P loss are higher when the P is applied during periods of high probability of rainfall and surface runoff or with significant snow cover. The probability of large runoff events typically is greatest in the spring due to snowmelt in northern areas and frequent high-intensity rainfall in most humid regions of the U.S.

Variable rate P application

Dense soil sampling from many fields has shown very large within-field spatial variability of soil-test P and crop yields. Precision agriculture technologies available to producers or custom applicators facilitate application of fertilizer and manure at rates adequate for different parts of a field based on soil-test P and estimated P removal. Iowa research has shown that grid or zone soil sampling methods combined with variable rate application of fertilizer or manure P may not always increase crop yield or increase profits compared with traditional application methods because the average effects on yield and amount of P applied depends on the overall level and distribution of soil-test P values. Also, soil testing seldom is performed on an annual basis, there is always a certain degree of sampling error (especially in fields with high small-scale variability), and research has shown that relationships between P removal and soil-test P are good over several years but not necessarily from year to year. Therefore, even with annual variable-rate application, use of this technology is not perfect. However, on-farm research has shown that variable-rate application of P fertilizer or P-based manure almost always minimizes or avoids P application to high-testing areas, reduces soil test P variability within fields, and, as a consequence improves P use efficiency and reduces risk of P loss by minimizing P application to high-testing field areas. Figure 6 shows, as an example, that use of variable-rate technology is an effective tool to manage P better. The change in soil-test P was measured after applying P-based liquid swine manure for corn after three corn-soybean rotation cycles. Similar results were observed with fertilizer application. In addition, variable-rate P application can be practically implemented on the basis of P-index ratings for field zones, not just based on soil test P or estimates of P removal. Variable rate application of fertilizer P is common in the Great Plains and the Corn Belt, and custom manure applicators also are beginning to apply manure at variable rates.

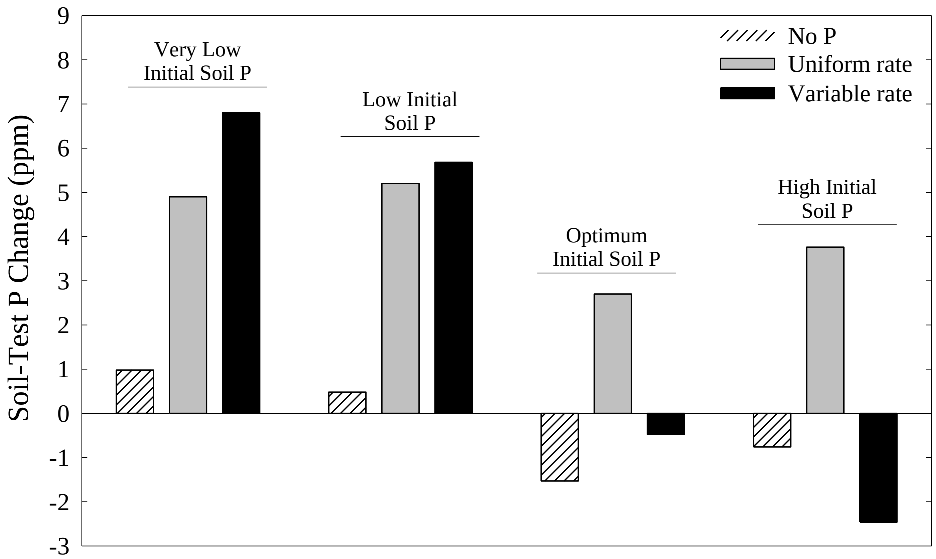

Figure 6. Effect of uniform application and soil-test phosphorus (STP) based variable-rate application of liquid swine manure on STP change within a field for various initial STP interpretation classes. Adapted from Mallarino, A.P., and J.S. Schepers. 2005. Role of precision farming in phosphorus management practices. p. 881-908. In T. Sims et al. (eds). Phosphorus: Agriculture and the Environment. Agronomy Series 46. ASA, CSSA, SSSAJ, Madison, WI.

Summary

Proper P management is essential for many reasons: to maximize the profitability of crop production, maximize efficiency of a non-renewable resource, reduce impacts of P use in crop production on surface water quality, and avoid increased regulation. Phosphorus management is somewhat simpler than for N in humid regions, due to differences in chemical transformations, no gaseous phase or volatilization, and less influence of environmental factors on processes that control crop-available forms and losses. Also, although the vast majority of P in soils is unavailable to plants because it is bound in insoluble P minerals or sorbed strongly to soil particles, soil sampling and testing is more reliable and useful than testing for N and other nutrients. The goal of sound P management in most regions of the U.S. should be to keep the soil-test P level at optimal ranges for maximum economic crop yield and utilize application methods and timing that optimize P use efficiency and economic profitability, and minimize water quality impairment.

Substantial within-field variability of P soil-test levels and P removal with harvest in most agricultural areas justifies the use of appropriate soil sampling, soil testing, application methods, and variable-rate application technology to increase P use efficiency and reduce the risk of P loss to water resources. The large variation across the U.S., and even within states, due to many factors means that best P management will also vary. Therefore, any list of best P management practices always will need to be tailored to a specific area, and likely will be incomplete in regard to meeting all potential P management issues. Following is a list that encompasses the most important concepts underlying P management strategies.

Management Practices for P Fertilization:

1. Sample soil as frequently and as densely within fields as economically possible and use appropriately calibrated soil-test methods based on research for each state or region.

2. Consider yield levels and crop P removal across and within fields to help maintain optimum soil-test P levels in conjunction with soil testing.

3. Fertilize P deficient soils using environmentally and economically sound agronomic guidelines. In general, soils testing ‘high’ or “very high” will not respond economically to additional P and should not receive fertilizer except for starter in certain known and specific conditions.

4. Divide large, non-uniform fields into smaller fertility management units based upon yield potential, soil tests, and relevant soil properties.

5. Credit all available P from manures and other organic sources when deciding the P application requirements for crop.

6. Refer to local research and guidelines concerning P placement methods to optimize P use efficiency, the profitability of nutrient application, and water quality protection.

7. Incorporate or inject high rates of inorganic or organic P sources into the soil where the risk of surface runoff or soil erosion is high.

8. Use manure nutrient analysis and a P risk assessment tool such as the P Index in order to utilize as much manure nutrients as much as possible without increasing the risk of P loss and water quality impairment.

Case Study

There are many different P management strategies for crop production that are used by producers across the U.S. It is impossible to give one example representative for all geographic areas, crops, and current management systems concerning options for improved P management. These would vary with soil type, crop, rotation, climate, available fertilizer or manure, application equipment, and producer management philosophy. The following example describes a P management system being used for a specific farm in the U.S. Corn Belt, and includes possible practices the producer could consider to improve crop use efficiency and economic return from P application while minimizing losses from fields that could impair water resources.

Example scenario

- A 1,000 acre farm in Western Iowa.
- Soils are prairie-derived, well drained, and formed in loess on convex slopes and ridges. In general topsoil texture is silty clay loam and slopes range from 0 to 15 percent.
- The farm has fields with continuous corn and corn rotated with soybean.
- The producer uses chisel-plow and disk tillage in about half of the fields and no-till in the other half, and he has not built terraces.
- The farmer has a large confined swine production operation. Liquid swine manure is broadcast in the fall after crop harvest and before soils freeze or are covered with snow. The manure is applied based on the manure N concentration and the corn N fertilization needs assuming 90% manure N availability as suggested by Iowa State University manure nutrients management guidelines (220 lb total N for continuous corn and 165 lb total N/acre for corn after soybean).
- The only P or K fertilizer applied in the farm is a small rate of N-P-K starter always applied for corn.
- Soil testing for P and K seldom is used.
- Potassium deficiency is not likely in this farm and in most of the western Iowa region because soils have naturally high soil-test K levels.

- In wet years, and especially in the fields with steeper slopes, the producer has noticed high surface runoff after rainfall events. He has implemented no-till management in the fields with the steepest slopes, but erosion can be observed in several fields.

This example scenario is not uncommon where nutrient management with manure is a challenge due to multiple nutrients and emphasizes the potential benefits from development of an improved P management plan. Following are some management options to consider. This set of agronomic practices is an example of a properly designed nutrient management plan and would contribute to increased crop production by enhancing P use efficiency and minimize environmental problems related to P losses.

- It is important from the agronomic and environmental perspectives to have an estimation of available soil P and K. This is crucial to adjust nutrient application rates in order to meet crop requirements and/or prevent water contamination issues. In this specific case, the producer should adopt a soil sampling and testing strategy because application of N-based manure for corn after soybean may apply sufficient P for the corn crop, but may supply insufficient P for the soybean crop or supply excessive amounts for the rotation. Or, if enough manure is not available to treat all fields, the low starter rate will not supply adequate P and K for high yielding crops.

- Application of an insufficient amount of manure nutrients will limit profitability and application of an excessive amount will increase soil P beyond optimum levels and will therefore increase the risk of P loss. With continuous corn, application of N-based manure each year undoubtedly will increase soil P to unacceptable levels concerning risk of P loss and water quality impairment. Soil sampling and testing strategies should be implemented based on either a zone sampling approach considering topography, soil map units, yield level, or other field information; or on a grid sampling approach, which in Iowa is based mostly on cells 2.5 acres in size. This information would allow the farmer to know what parts of the farm or fields do not require additional P application, where additional P is needed, or where soil P test levels are so high that there is a risk to water quality. The frequency of soil sampling should be not less than 4 years; ideally every 2 years for the corn-soybean rotation and also the same frequency for continuous corn given the high P loads with annual manure application.

- Once soil P tests results are available, the next step is to plan manure application priorities in order to improve as much as possible use of the manure P resource for crop production profitability, and minimize chance of soil P buildup to levels above optimum for crops. According to Iowa State University swine manure P has 90 to 100% availability for crops.

Therefore, the producer should continue applying manure in fields or field areas with optimum or lower P levels, which most likely will be for some of the fields managed with a corn-soybean rotation. This allocation may also require manure be hauled to fields that historically have less frequent manure application. Because N-based manure rates applied to corn almost always supply sufficient P for the corn crop, complementary inorganic P fertilizer may be needed for the soybean crop. The producer also should avoid or reduce manure applications in areas with already high P tests, and apply additional inorganic N fertilizer for corn as needed. If there is large within-field variation in soil-test P levels, the producer could use variable-rate manure and fertilizer application equipment to improve nutrient management within fields.

- The risk of P loss with runoff can be also reduced, and the manure-N use efficiency can significantly be increased, by injecting the manure instead of broadcast applying in fields with no-till management. Also, the producer could use low soil disturbance coulters and knives, which are becoming more available and affordable, to further minimize soil erosion and P loss. And, any P fertilizer needed for soybean in low-testing no-till areas could be applied in subsurface bands, either with planter starter attachment or deep-banding before planting. Iowa research shows that P banding seldom increases crop yield compared with a broadcast application in no-till, but this practice can reduce the risk of P loss with surface runoff.

- If the producer still wants to apply manure in areas testing above optimum, he should use the Iowa P Index to determine if applying additional P to those areas increases the risk of P loss to unacceptable levels. Using the P Index will indicate if additional P can be applied, and if it can be applied, it will suggest the most effective soil or P management practices to assure the risk of P loss does not increase. Given the conditions for this farm (sloping ground), controlling erosion and surface runoff should be the most effective way of decreasing P loss. The adoption of terraces, contour cropping, and/or no-till in additional fields with surface runoff would reduce erosion and P loss, and also will increase the agronomic efficiency of the production system and over time perhaps the profitability of the system as well.

- The producer should also evaluate the possibility of eliminating the application of starter P in areas with high P soil tests, especially with the corn-soybean rotation, because the low probability of grain yield increases from starter P in those conditions.